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3 μm diode lasers grown on (Al)GaInSb compositionally graded metamorphic buffer layers

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Abstract
Diode lasers operating at 3 μm in continuous wave mode at room temperature were fabricated using metamorphic molecular beam epitaxy. The laser heterostructures have a lattice constant 1.3–1.6% bigger than that of the GaSb substrates. The mismatch between the epi-structure and the substrate lattice constants was accommodated by a network of misfit dislocations confined within linearly compositionally graded buffer layers. Two types of the buffers were tested—GaInSb and AlGaInSb. The laser heterostructures with Al-containing buffer layers demonstrated better surface morphology and produced devices with lower threshold and higher efficiency. At the same time the use of Al-containing buffers caused an excessive voltage drop across the laser heterostructure. Thus, a maximum continuous wave output power of 200 mW was obtained from lasers grown on GaInSb buffers, while only 170 mW was obtained from those grown on AlGaInSb buffers.

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Introduction

High-power diode lasers operating at near and above 3 μm wavelengths at room temperature (RT) in continuous wave (CW) mode are in demand for a variety of applications in military, industrial and medical areas. Recent reports on the development of these devices have shown that Auger recombination does not preclude the CW RT operation of mid-infrared diode lasers [1–4]. In fact, low threshold current densities of about 200 A cm^{-2} obtained for 3 μm diode lasers revealed a bonus of the narrow bandgap quantum wells (QWs) for laser development arising from the low density of states [5]. This fundamental advantage became apparent in experiments after the issue of insufficient hole confinement in active GaInAsSb quantum wells (QW) [6] was resolved. The hole confinement was improved after the quaternary AlGaAsSb barrier material was replaced with the quinary AlGaInAsSb alloys [7]. Using a five-component alloy enabled independent control over the valence and conduction band edge positions in the barrier material. Similar flexibility in the design of the QWs is expected to open novel band engineering opportunities to optimize laser heterostructures for improved CW RT operation and extended wavelength range. One possible way to acquire this flexibility is to establish a growth technology that allows treating the lattice parameter of the device heterostructure as a design variable. In classical diode laser technologies the lattice parameter is imposed by the lattice constant of the available substrate. This restriction can be removed by growing compositionally graded buffer layers to mediate the lattice mismatch between the substrate and the device heterostructure [8, 9]. This approach was successfully used to extend the wavelength range of GaAs-based diode lasers [10, 11].

In this work, we discuss 3 μm diode lasers grown on GaSb substrates using compositionally graded buffer layers. The laser heterostructures designed and implemented have a lattice parameter 1.3–1.6% larger than that of GaSb. Compatibility of this type of metamorphic growth with high-power diode laser technology was demonstrated in our previous report on As-free 2.2 μm diode lasers [12], where we studied heterostructures having lattice parameters about 0.8–0.9%

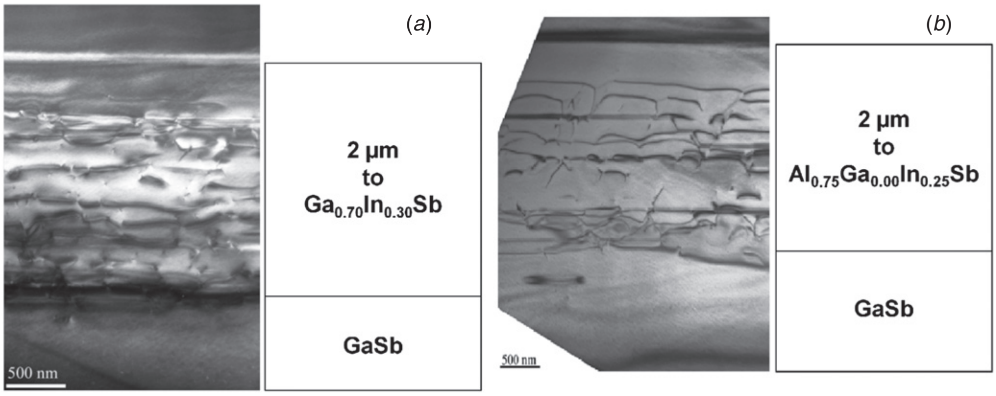

Figure 1. Cross-sectional TEM images of samples with 2 μm thick lineraly graded composition buffers grown onto GaSb substrates: (*a*) GaInSb with top In content of 30%; (*b*) AlGaInSb with top Al, Ga and In contents of 75, 0 and 25% respectively.

larger than that of the GaSb substrate. The corresponding device output power and threshold current densities were close to those of pseudomorphic lasers; therefore using the metamorphic approach imposed minimal to no effect on the laser performance. It should be noted that other approaches to metamorphic molecular beam epitaxy of laser heterostructures exist [13–16]. This particular work deals with further development of the approach to metamorphic growth based on compositionally graded buffer layers but attempts no comparison to alternative techniques.

Compositionally graded buffers

Epitaxial growth was performed on Te-doped (0 0 1) GaSb substrates in a Veeco GEN-930 solid-source molecular beam epitaxy (MBE) system equipped with antimony and arsenic valved cracker sources. The substrate temperature was controlled by BandIT (K-space) in pyrometer mode. A growth rate of about 1 monolayer per second was used throughout the entire growth. After the standard procedure of the thermal surface oxide removal, the reflected high-energy electron diffraction (RHEED) pattern indicated a clear (1×3) reconstructed surface with strong Kikuchi lines. A 500 nm GaSb buffer layer was grown at 530 °C, and then the substrate temperature was reduced down to ~460 °C under a Sb flux.

Two metamorphic laser heterostructures were designed and fabricated. Lattice parameters of these laser heterostructures were about 1.3 and 1.6% larger than those of the GaSb substrate. The lattice constant mismatch between substrate and laser heterostructure was accommodated by formation of misfit dislocations in the compositionally graded buffer layers. Two different buffer layers were used: GaInSb and AlGaInSb. For the $Ga_{1-x}In_xSb$ buffer layer the In composition was graded from $x = 0$ to 0.3. For the $Al_{1-x-y}Ga_yIn_xSb$ buffer layer, the Al was graded from 0 to 0.75, the Ga from $y = 1$ to 0, and In from $x = 0$ to 0.25. The compositional grading was designed to produce a nominally linear change of the lattice constant over the whole 2 μm of the graded buffer thickness. The resulting rate of the compressive strain increase in corresponding hypothetical unrelaxed material was about 0.9–1% μm^{-1}.

Figure 1 shows cross-sectional transmission electron microscopy (XTEM) images taken for epi-structures having compositionally graded buffers topped with a 500 nm thick unstrained and unrelaxed layer that serves as a ‘virtual substrate’ for the further growth of the device heterostructure. Strain relieving misfit dislocations forms in the buffer layer. The topmost portion of the buffer layer (about 400 nm as estimated from TEM) remains dislocation free and, hence, compressively strained [9]. Thus one should differentiate between the in-plane and in-growth-direction lattice parameters on top of the buffer layer. The lattice constant of the device heterostructure is intended to match the in-plane lattice parameter on top of the buffer layer. Figure 1 shows that the topmost section of the graded buffer and the ‘virtual substrate’ are dislocation free within the field of view available in XTEM; therefore the threading dislocation density is below 10^7 cm^2.

The values of in-plane lattice parameters on top of the graded buffer layers were obtained from reciprocal space maps (RSM) measured near the symmetric (0 0 4) and asymmetric (3 3 5) Bragg reflections. The RSM for symmetric and asymmetric reflexes were measured at different azimuth angles to identify the possible tilt in the metamorphic buffers. We find that the epi-structures with either the GaInSb or AlGaInSb compositionally graded buffer layer are tilted toward the [1 1 0] direction (crystallographic orientation was determined based on GaSb wafer major and minor flats markings).

Figure 2 shows the (0 0 4) RSMs for two laser heterostructures grown on (*a*) GaInSb and (*b*) AlGaInSb buffers measured along the [1 1 0] direction. The separation in the [1 1 0] direction between the substrate and epi-structure reflexes denotes the corresponding tilt angle. The tilt angle increases almost linearly with thickness in the bottom part of the graded buffer, i.e. in the part of the buffer layers containing dislocations (figure 1). It can be concluded that a small amount of the lattice mismatch in one of the directions is accommodated through the tilting of the metamorphic layers. The average tilt angle is about 0.45° in structure (*a*) and 0.15° in structure (*b*). The lateral spread in the reflexes from the laser cladding layers can be ascribed to the mosaic effect.

Figure 3 shows (3 3 5) RSMs measured in the [1 1 0] directions (minimal tilt effect). The reflexes from the

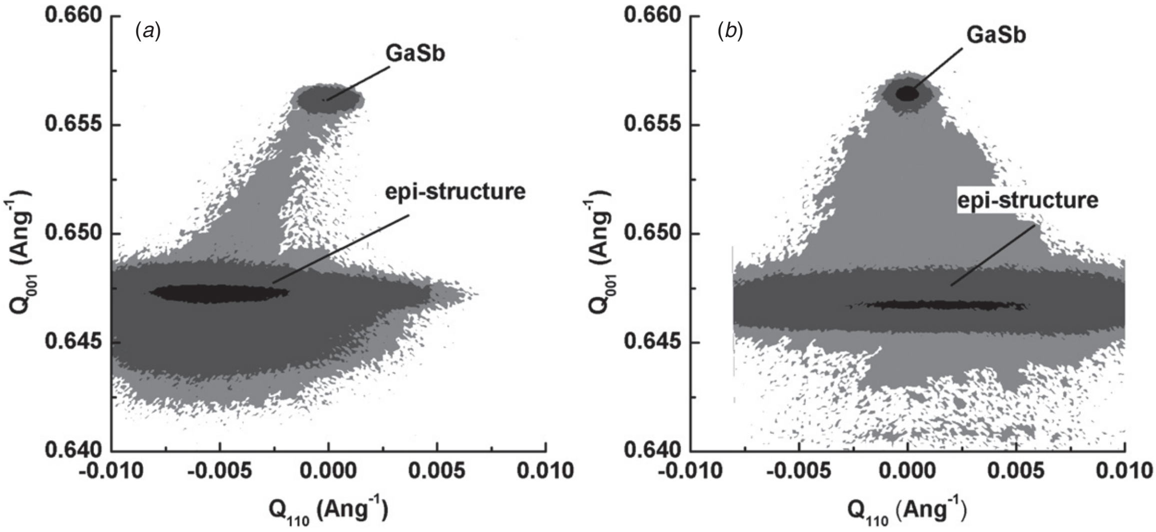

Figure 2. Symmetric (0 0 4) RSMs measured for laser heterostructures grown on (*a*) GaInSb and (*b*) AlGaInSb compositionally graded buffer layers along the [1 1 0] direction. The azimuth angle was chosen to emphasize the tilt in the epi-structure.

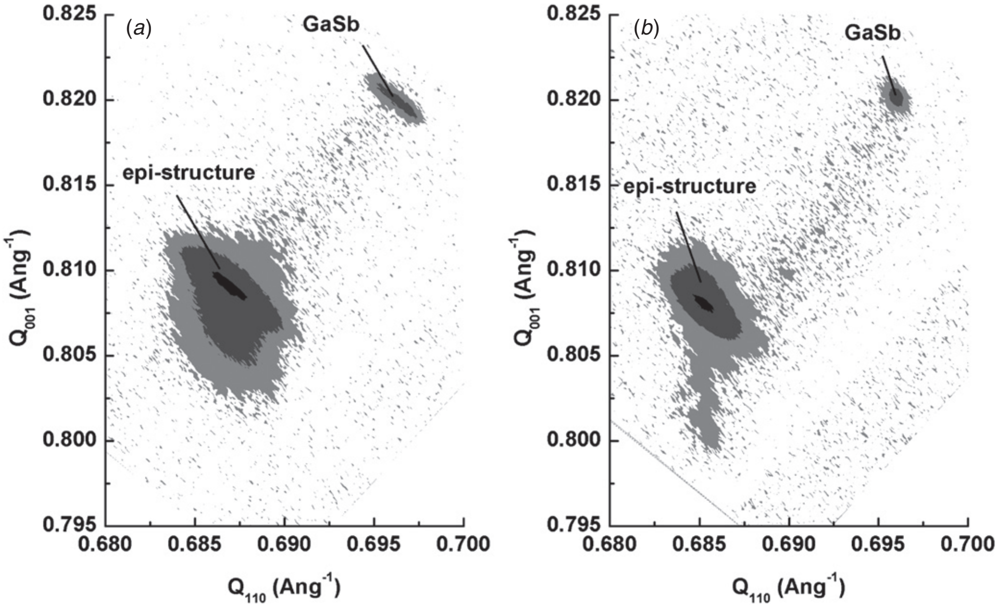

Figure 3. Asymmetric (3 3 5) RSMs measured for laser heterostructures grown on (*a*) GaInSb and (*b*) AlGaInSb compositionally graded buffer layers along the [1 1 0] direction (minimal tilt effect).

compositionally graded buffer layers correspond to about 95% relaxation in the bottom part (about 70% of total thickness of the buffer) of the buffer and 0% relaxation in the top portion of the buffers. The in-plane lattice parameter at the top of the GaInSb and AlGaInSb buffer layers was 1.3% and 1.6% larger than that of GaSb buffers, respectively. The laser heterostructures were nearly lattice matched to these in-plane lattice parameters with marginal strains of about 0.1%.

Metamorphic laser heterostructures

The laser's active regions contained three 10 nm GaInAsSb QWs having a nominal In composition of 55%. The As composition varied slightly between two structures but remained within the range of 8–10%. The compressive strain in the QWs was in the range 1.3–1.5%, as estimated from HRXRD. The QWs were spaced by 50 nm AlGaInAsSb barriers having nominal Al and In contents of 20 and 32%, respectively; the As content of the barrier alloys was in the range of 8–10% for both structures. The waveguide core consisted of an active triple-QW region sandwiched between 300 nm barrier layers. Schematic band diagrams of the laser heterostructures calculated using data from reference [17] and adopting the interpolation scheme from [18] are shown in figure 4. The valence band bowing coefficient was taken to be zero due to a lack of comprehensive experimental information. The estimated conduction and valence band discontinuities between the QW and barrier alloys are 200 and 150 meV, i.e. presumably sufficient to confine both types of carriers within the active QWs.

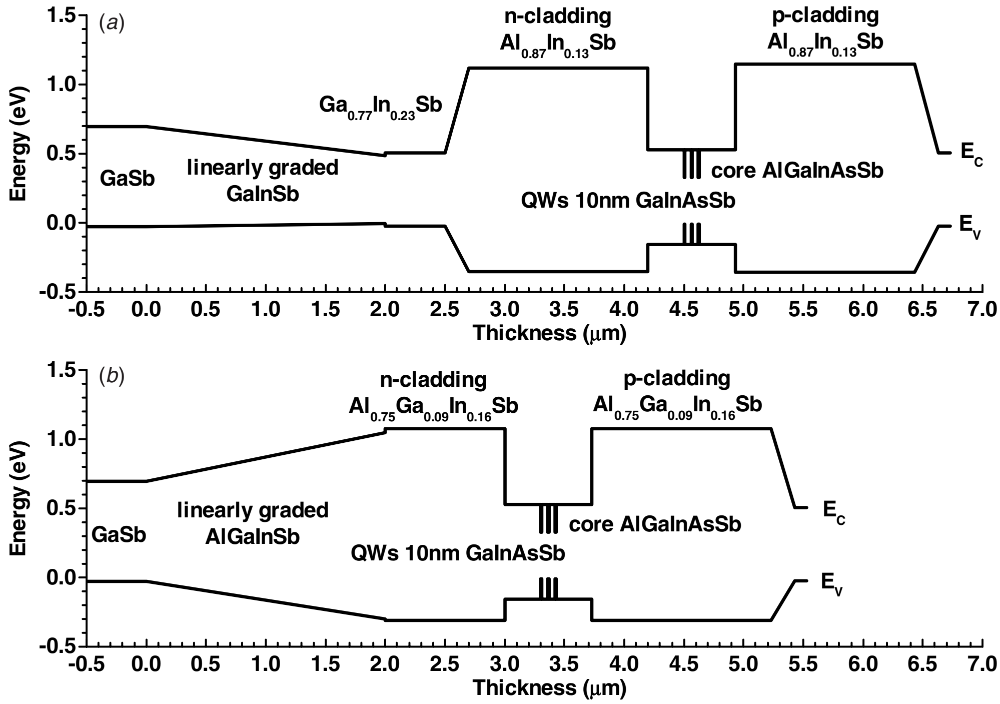

Figure 4. Calculated band diagram of the metamorphic laser heterostructures grown on (*a*) GaInSb and (*b*) AlGaInSb compositionally graded buffer layers.

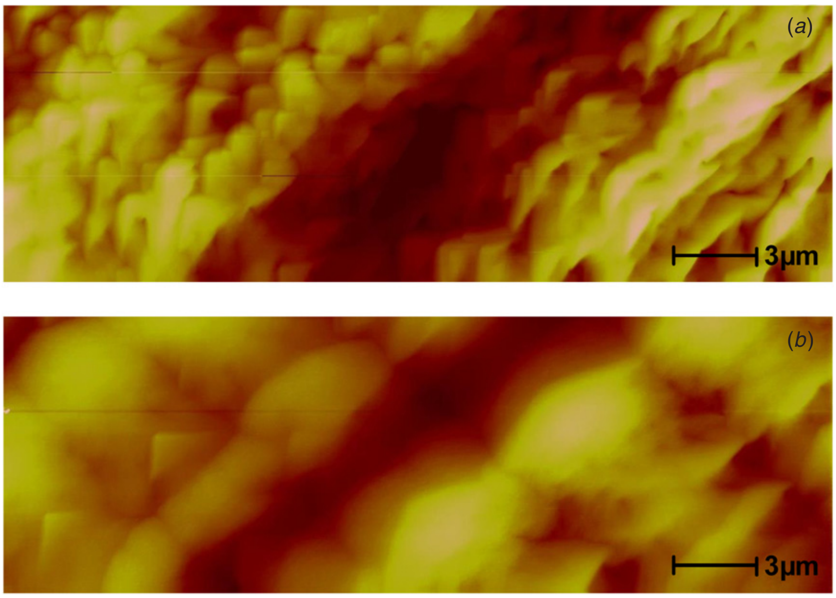

Figure 5. AFM images of the wafers with laser heterostructures grown on top of (*a*) GaInSb and (*b*) AlGaInSb compositionally graded buffer layers.

Cladding layers were made of $Al_{0.87}In_{0.13}Sb$ for laser heterostructures grown onto GaInSb graded buffer layers. Figure 4(*a*) illustrates that the carrier transport considerations require an additional compositionally graded layer to assist electron injection from the substrate into the n-cladding layer. This was achieved by growing a ∼200 nm thick AlGaInSb graded composition n-doped layer. In the case of the structure grown onto the AlGaInSb graded buffer, no additional compositional grading was necessary and the $Al_{0.75}Ga_{0.09}In_{0.16}Sb$ itself was used as cladding material (figure 4(*b*)). Thus it appears that the utilization of AlGaInSb rather than GaInSb compositionally graded buffers is more natural for diode laser development. Furthermore, atomic force microscopy (AFM) analysis demonstrates that compositionally graded buffer layers consisting of AlGaInSb have a smoother surface than those consisting of GaInSb. Figure 5 shows AFM images of the wafers with laser heterostructures grown on GaInSb (*a*) and AlGaInSb (*b*) compositionally graded buffer layers. The structure grown onto AlGaInSb shows a smoother surface in between the

grooves of the cross-hatch pattern compared to the one grown onto GaInSb. RMS roughness over the area of 30 by 10 μm was 4.3 nm for AlGaInSb buffer and 5.8 nm for GaInSb one.

Diode laser fabrication and characterization

Each wafer was processed into 100 μm wide, dielectrically confined ridge waveguide lasers. The ridge waveguides were fabricated by wet-etching of the cap and the p-cladding layers outside of the current stripe. Uncoated devices were used for initial pulse testing (200 ns/100 kHz) and for gain/loss measurements. For CW characterization the laser chips were coated to reflect below 5% (antireflection (AR)) and above 95% (high reflection (HR)). The 2 mm long coated devices were In-soldered epi-side down onto gold-plated polished copper blocks.

Figure 6(*a*) shows the light–current characteristics of the 1 mm long uncoated lasers using both types of metamorphic buffers as well as of the pseudomorphic devices reported previously [4]. The threshold current densities were lower for devices grown onto AlGaInSb buffers, i.e. for devices made of wafers with better surface morphology. The value of the threshold current density was about 300 A cm^{-2}, i.e. only 50% higher than that obtained for 3 μm emitters grown in a pseudomorphic manner and with a double-QW active region. The external efficiency of the lasers grown onto AlGaInSb buffer layers was better that that of lasers grown onto GaInSb, namely 39 versus 34%. It should be noted that external efficiency of metamorphic lasers grown onto AlGaInSb buffers is nearly the same as that of 3 μm pseudomorphic lasers [4].

Figure 6(*b*) shows the gain spectra measured by the Hakki–Paoli technique at different underthreshold currents for lasers grown on AlGaInSb buffers. The total optical loss was about 17 cm^{-1} as estimated from the long wavelength part of the gain spectra where the material gain is zero. Thus the internal optical loss is about 5 cm^{-1}, assuming mirror loss for uncoated 1 mm long lasers of about 12 cm^{-1}. The injection efficiency can be estimated to be about 55%. The values of internal loss and injection efficiency are the same as measured previously for pseudomorphic lasers emitting near 3 μm [4]. The transparency current density can be estimated to be about 50 A cm^{-2} per QW, corresponding to an $\sim$20% increase from what was measured for pseudomorphic devices. The rate of increase of the peak gain with current is about 85 cm^{-1} A^{-1}, which is 15–20% lower than that reported for $\lambda = 3$ μm pseudomorphic devices [5]. It is not apparent if this $\sim$20% parameter degradation is a consequence of the defect formation related to metamorphic growth. The observed small difference can be explained by unintentional QW band design variation, e.g. the record pseudomorphic 3 μm emitters have higher QW compressive strain (1.7% versus 1.3–1.5% here) and a larger estimated valence band barrier (180 meV versus $\sim$150 meV here). Due to a lack of experimental information, further detailed band engineering of the metamorphic laser heterostructures was not possible and all estimations can serve only as general design guidance.

The Hakki–Paoli analysis of the gain spectra of diode lasers grown onto GaInSb buffer layers was not possible using our experimental approach based on spatial mode filtering. We were unable to obtain sufficient Fabri–Perot resonator contrast, presumably due to strong scattering of multiple optical modes on structural defects revealing themselves in poor surface morphology (figure 5). Thus variable cavity length analysis was applied to the lasers grown onto GaInSb buffers. Internal optical losses were estimated to be 7–8 cm^{-1} from the least

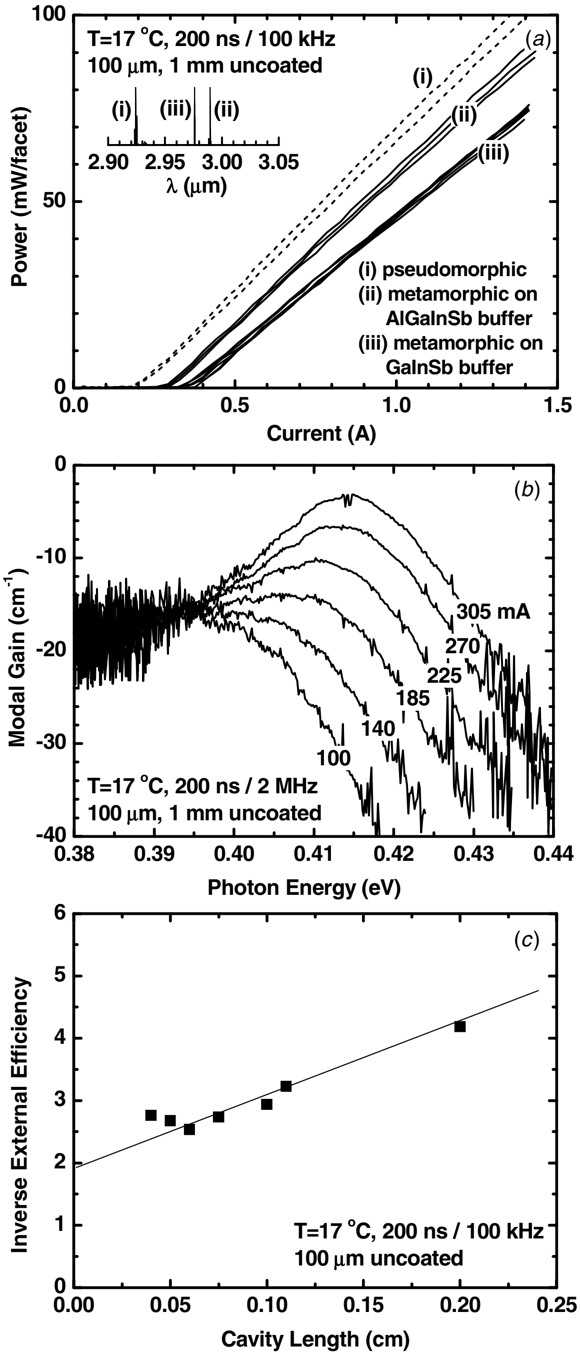

Figure 6. (*a*) Light–current characteristics of the 1 mm long uncoated lasers grown pseudomorphically on GaSb and on GaInSb and AlGaInSb compositionally graded buffer layers. (*b*) Current dependence of the modal gain spectra for 1 mm long, 100 μm wide, uncoated lasers grown on AlGaInSb buffer measured in the pulsed regime (200 ns/2 MHz). (*c*) Cavity length dependence of the inverse external efficiency for lasers grown on GaInSb buffers.

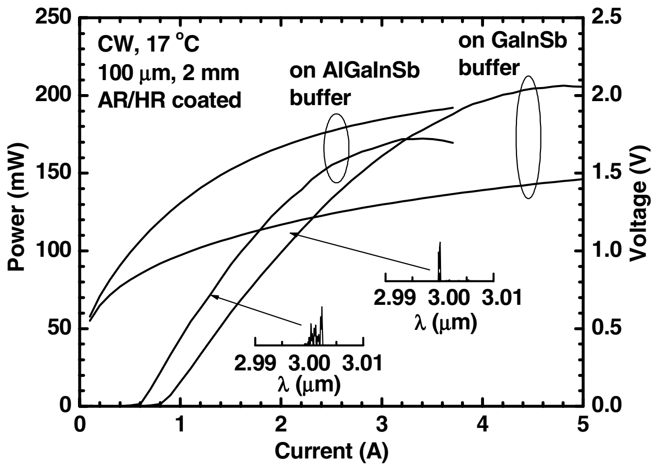

Figure 7. Light–current characteristics measured in the CW regime at 20 °C for 2 mm long, 100 μm wide, AR/HR-coated diode lasers grown on GaInSb and AlGaInSb compositionally graded buffer layers.

square linear fit of the dependence of the inverse external efficiency on the inverse mirror loss for cavity lengths in the range from 0.6 to 2 mm (figure 6(*c*)). The estimated injection efficiency was similar to that of lasers grown onto AlGaInSb buffers. Thus we conclude that the reduced efficiency and increased threshold in devices made of metamorphic laser heterostructure grown onto the GaInSb graded buffer originate from the extra ~3 cm^{-1} of internal loss. The extra optical loss compared to devices grown onto AlGaInSb buffers can be associated with scattering due to structural defects. Possible extra scattering loss is indirectly supported by observed adverse surface morphology of wafers grown onto GaInSb buffers and abnormal complications with mode filtering in corresponding devices in Hakki–Paoli experiments.

Figure 7 is a plot of the CW light–current–voltage characteristics of the 2 mm long AR/HR coated lasers. The devices grown onto AlGaInSb again demonstrate lower threshold and better initial efficiency. However, the voltage drop across the laser heterostructure is substantially lower in the device grown onto the GaInSb buffer. Thus, despite having better threshold and efficiency, the devices grown onto AlGaInSb graded buffers demonstrate lower maximum CW output power, namely 170 mW versus above 200 mW obtained for devices grown onto GaInSb. The nature of the extra voltage drop across the laser heterostructure grown onto AlGaInSb buffers can be associated with peculiarities of the doping and/or carrier transport in relaxed buffer layers [19]. Possible explanation includes the large activation energy of the Te dopants in AlGaInSb layers with In composition in the range from 15 to 25% [20].

Summary

The 3 μm diode lasers were grown metamorphically on GaSb substrates using linearly compositionally graded buffer layers. The laser heterostructure lattice constant was increased by 1.3–1.6% above that of GaSb. The transmission electron microscopy analysis revealed efficient confinement of the misfit dislocation network within the compositionally graded buffer layers. Both GaInSb and AlGaInSb buffer layers were investigated. AlGaInSb graded buffer layers have improved surface morphology, and produced devices with better threshold and efficiency, and allowed the growth of thinner laser heterostructures. However, transport through AlGaInSb strain relaxed layers appears to be more problematic than that through GaInSb and devices grown onto AlGaInSb demonstrate an extra 0.5 V of voltage drop at the maximum output power level. The lasers demonstrated state-of-the-art performance parameters with more than 200 mW of CW output power at room temperature from 100 μm apertures. Low threshold current densities of about 300 A cm^{-2} were observed for metamorphic lasers.

Acknowledgments

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